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Development of an Analytical Tool to Study Power Quality of AC Power Systems for Large Spacecraft

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DEVELOPMENT OF AN ANALYTICAL TOOL TO STUDY POWER QUALITY OF AC POWER SYSTEMS FOR LARGE SPACECRAFT

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ABSTRACT

Power quality in AC power system depends on the harmonic content of the waveform. To accurately predict the content of harmonic components in a particular system configuration, an engineer needs the analytical tools to predict the behavior of the various harmonic components. This paper describes a harmonic power flow program applicable to space power systems with sources of harmonic distortion. The algorithm is a modification of EPRI's HARMFLO program which assumes a three phase, balanced, AC system with loads of harmonic distortion. The modified power flow program can be used with single phase, AC systems.

Early results indicate that the required modifications and the models developed are quite adequate for the analysis of a 20 kHz testbed built by General Dynamics Corporation (GDC). This is demonstrated by the acceptable correlation of the present results with published data. Although the results are not exact, the discrepancies are relatively small.

INTRODUCTION

As the size of spacecraft has grown over the years, so has the demand for electrical energy consumed by these vehicles. In the first manned spacecraft, Mercury, the power supply was a low capacity, 24 VDC system. As the plans for the vehicle needed to reach Mars indicate, there must be more capability to support more people and more equipment for a much longer period of time than any of the previous projects have in the past. This capability is greatly enhanced by an AC system. The proposed high frequency 20 kHz system [1] has the advantages of high efficiency and reliability, minimum overall system weight, and easy system growth. Although an AC system can solve the power demand problem, it can cause problems which must be addressed to assure an efficient, reliable power supply.

A potential problem with an AC system is harmonic resonance. Since the proposed source of the 20 kHz, AC wave is an inverter and the system will supply various nonlinear loads among others, harmonic resonance is a possible occurrence. Computer software is required to study this phenomenon so that proper filtering can be designed for its elimination.

Voltage and current resonance in a power system can cause many serious problems. These include:

- insulation failure due to overvoltage,
- false instrumentation data due to multiple zero crossings of the waveform,
- current overload in lines and other components,
- rf noise, and
- malfunction of electrical equipment due to high frequency signals in the power supplied.

Other problems created by low power quality in the power supply system may exist. However, the above problems are intended to demonstrate the reason for concern over harmonic resonance.

A reasonable method for identifying and evaluating resonance problems in a proposed power system is to use a harmonic power flow program such as HARMFLO developed by the Electric Power Research Institute (EPRI). HARMFLO can predict steady-state resonance conditions in three phase, balanced power systems at 60 Hz.

This paper discusses a modified harmonic power flow algorithm for use with mainly spacecraft power systems. Unlike its terrestrial counterpart used for a balanced, three phase, 60 Hz system with loads of harmonic distortion, the algorithm described here is applicable to a high frequency, single phase, AC system with a source of harmonic distortion.

THE HARMONIC POWER FLOW ALGORITHM

The HARMFLO algorithm, developed by Dr. G. T. Heydt [2,3] of Purdue University, uses a modified version of the standard Newton-Raphson formulation for a power flow solution. The modification involves the alteration of the voltage vector to include all of the harmonic components to be examined not just the non-triple odd harmonics typically found in three phase balanced power systems. Also, non-existent models of components such as the Mapham inverter and a single phase rectifier have been added. The voltage vector becomes

$$[V^{(1)}, \dots V^{(l)}, \dots V^{(n)}, \Phi]^T$$

where $V^{(i)}$ is the set of ith harmonic bus voltages and Φ represents the firing and commutation angle of any three phase rectifiers. The formulation of the harmonic power flow also

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requires the modification of the scheduled quantities to include those produced by the inverters.

$$\Delta I^{(I)} = I^{(I)\,scheduled} - I^{(I)\,calculated}$$

where $I^{(i)\,scheduled}$ is the scheduled i^{th} harmonic current at each bus, and $I^{(i)\,calculated}$ is the calculated i^{th} harmonic current at each bus.

The process also requires the modification of the Jacobian matrix to

$$[J] = \begin{bmatrix} J^{(1)} & J^{(2)} & \cdots & J^{(n)} & 0 \\ TG^{(2,1)} & TG^{(2,2)} & \cdots & TG^{(2,h)} & H^{(2)} \\ \cdot & \cdot & \cdots & \cdot & \cdot \\ TG^{(h,1)} & TG^{(h,2)} & \cdots & TG^{(h,h)} & H^{(h)} \\ TG^{(1,1)} & TG^{(1,1)} & \cdots & TG^{(1,h)} & H^{(1)} \end{bmatrix}$$

where

$$J_{ij}^{(m)} = \begin{bmatrix} \dfrac{\partial P_i^{(m)}}{\partial V_j^{(m)}} & \dfrac{\partial P_i^{(m)}}{V_j \partial \delta_j^{(m)}} \\[2ex] \dfrac{\partial Q_i^{(m)}}{\partial V_j^{(m)}} & \dfrac{\partial Q_i^{(m)}}{V_j \partial \delta_j^{(m)}} \end{bmatrix},$$

$$TG_{ij}^{(m,n)} = \begin{bmatrix} \dfrac{\partial Re(I_i^{(m)})}{\partial V_j^{(n)}} & \dfrac{\partial Re(I_i^{(m)})}{\partial \delta_j^{(n)}} \\[2ex] \dfrac{\partial Im(I_i^{(m)})}{\partial V_j^{(n)}} & \dfrac{\partial Im(I_i^{(m)})}{\partial \delta_j^{(n)}} \end{bmatrix},$$

and

$$H_{ij}^{(m)} = \begin{bmatrix} \dfrac{\partial Re(I_i^{(m)})}{\partial \alpha_j} & \dfrac{\partial Re(I_i^{(m)})}{\partial \beta_j} \\[2ex] \dfrac{\partial Im(I_i^{(m)})}{\partial \alpha_j} & \dfrac{\partial Im(I_i^{(m)})}{\partial \beta_j} \end{bmatrix}.$$

Thus, this modified HARMFLO differs from others which use the fundamental power and harmonic current responses of the nonlinear devices to solve the voltage levels within the power system [4]. Also, it differs from the use of ATP (Alternate Transients Program) version of the Electromagnetic Transient Program (EMTP) to perform harmonic analysis in which nonlinear loads are represented by harmonic current injections at desired nodes within the power system [5].

MODIFICATION TO THE HARMONIC POWER FLOW ALGORITHM

The original harmonic power flow algorithm, HARMFLO, cannot be used directly for the study of spacecraft power systems for two major reasons. The first reason is that the algorithm, as developed, is designed strictly for three phase, balanced power systems rather than single phase systems. Secondly, only loads, but not the power sources, can be sources of harmonic distortion. Both of these assumptions are adequate for terrestrial power systems. However, spacecraft power systems are designed to be single phase with solid state DC-AC inverters. These potential harmonic sources imply the need for modifications to the basic algorithm of HARMFLO.

The modifications needed to handle all harmonic components are relatively simple. They comprise redimensioning of the matrices, and adjustment of pointers in the algorithm to assure the exclusion of undesired harmonics from the analysis.

The harmonic power flow algorithm assumes that all AC power is supplied by balanced, three phase sinusoidal sources. However, a potential power source for spacecraft can be an AC source which embodies DC-AC solid state inverters. The most commonly cited AC source to employ the resonant type of operation is the Mapham inverter [6] shown in Figure 1. The Mapham inverter, popular due to its simplistic, light weight design
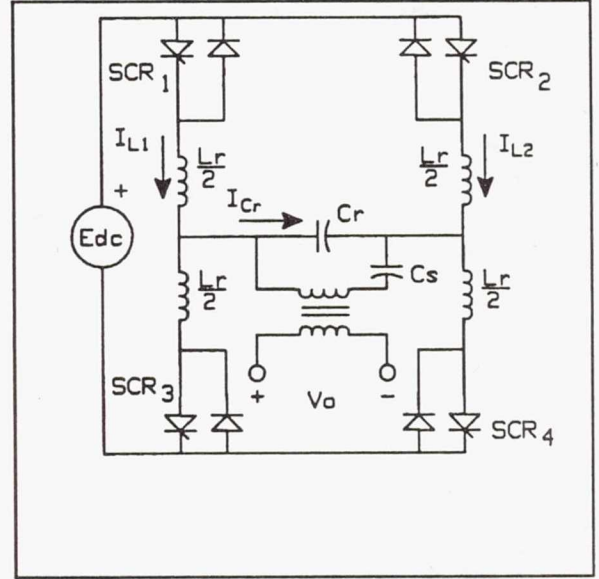

Figure 1 - Circuit diagram of a Mapham Inverter.

and good regulation, employs an L-C series combination to produce a dampened AC waveform. The SCR's are used to reverse the current on every half cycle to keep the inverter producing AC power. The resulting output of this type of inverter is shown in Figure 2. The discontinuities in the waveform indicate that this power source can cause harmonic distortion. This means that, to use HARMFLO in this application, the Mapham inverter must be modelled in the harmonic power flow algorithm. The required modifications for modelling such a power source are relatively more complex.
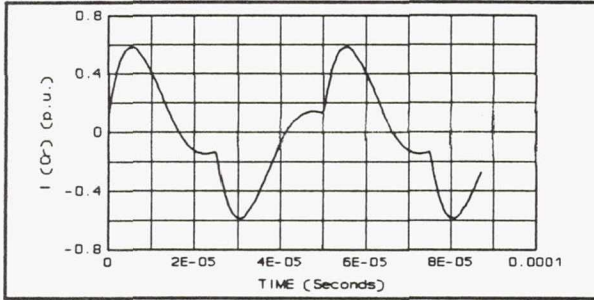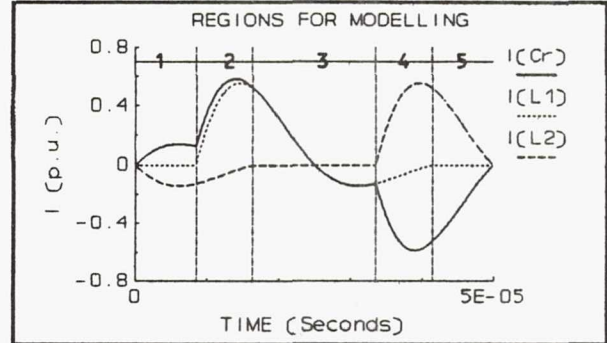
Figure 2 - Total Current Through Capacitor C_r.

Figure 4 - Capacitor Current, I_{Cr}; Inductor Currents, I_{L1} and I_{L2} with Indicated Regions for Modelling.

MODELLING THE MAPHAM INVERTER

The modelling of this type of device requires the computation of the scheduled magnitude and phase angle of each harmonic current component at each iteration. The first step in this process is to find the resonant frequency of the RLC circuit formed by the Mapham inverter and the power system. The power system equivalent determined at the terminals of the Mapham inverter is added to the inverter model as shown in Figure 3. Ordinary circuit
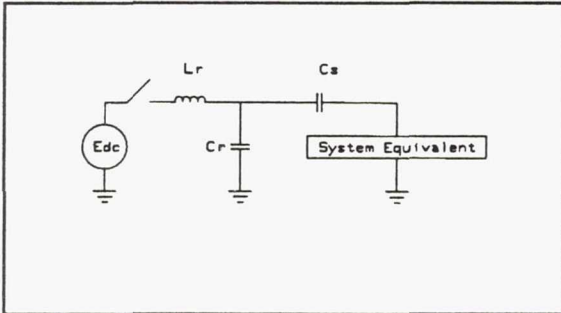

Figure 3 - Circuit Equivalent Used to Find Natural Frequency of System.

analysis techniques, such as Laplace transforms, can be used to find τ_r and ω_r, which are the time constant and frequency, respectively, of the natural response of the circuit.

The values of τ_r and ω_r can then be used to find an analytical representation of one period of the current waveform. This is accomplished by dividing a period of the waveform into regions defined by the physical characteristics of the waveform. Since the Mapham inverter is operated by firing the SCR's for the next half cycle before the conducting SCR's have commutated, the current waveform is defined by five distinct regions as shown in Figure 4. The resulting analytical expressions for each of the regions shown in Figure 4 are:

1. SCR_2 and SCR_3 are conducting and SCR_1 and SCR_4 are off,

$$I_{C_r}(t) = -I_o e^{-\alpha\left(t + \frac{\tau_r}{2}\right)} \sin(\omega_r t + \pi)$$

$$\text{for } 0 \leq t < \frac{\tau_s - \tau_r}{2} ;$$

2. SCR_1, SCR_2, SCR_3, and SCR_4 are conducting,

$$I_{C_r}(t) = I_o e^{-\alpha\left(t - \frac{\tau_s - \tau_r}{2}\right)} \sin\left[\omega_r t - \pi\left(\frac{\tau_s - \tau_r}{\tau_r}\right)\right]$$

$$- I_o e^{-\alpha\left(t + \frac{\tau_r}{2}\right)} \sin(\omega_r t + \pi)$$

$$\text{for } \frac{\tau_s - \tau_r}{2} \leq t < \frac{\tau_r}{2} ;$$

3. SCR_1 and SCR_4 are conducting and SCR_2 and SCR_3 are off,

$$I_{C_r}(t) = I_o e^{-\alpha\left(t - \frac{\tau_s - \tau_r}{2}\right)} \sin\left[\omega_r t - \pi\left(\frac{\tau_s - \tau_r}{\tau_r}\right)\right]$$

$$\text{for } \frac{\tau_r}{2} \leq t < \tau_s - \frac{\tau_r}{2} ;$$

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4. SCR_1, SCR_2, SCR_3, and SCR_4 are conducting,

$$I_{C_r}(t) = I_o e^{-\alpha\left(t - \frac{\tau_s - \tau_r}{2}\right)} \sin\left[\omega_r t - \pi\left(\frac{\tau_s - \tau_r}{\tau_r}\right)\right]$$

$$- I_o e^{-\alpha\left(t - \tau_s + \frac{\tau_r}{2}\right)} \sin\left[\omega_r t - \pi\left(\frac{2\tau_s - \tau_r}{\tau_r}\right)\right]$$

$$\text{for } \tau_s - \frac{\tau_r}{2} \le t < \frac{\tau_s + \tau_r}{2} \text{ and ;}$$

5. SCR_2 and SCR_3 are conducting and SCR_1 and SCR_4 are off,

$$I_{C_r}(t) = -I_o e^{-\alpha\left(t - \tau_s + \frac{\tau_r}{2}\right)} \sin\left[\omega_r t - \pi\left(\frac{2\tau_s - \tau_r}{\tau_r}\right)\right]$$

$$\text{for } \frac{\tau_s + \tau_r}{2} \le t < \tau_s ,$$

where α is the damping coefficient; τ_s is the period of the system frequency. The value of I_o is determined at each iteration. However, since the system configuration is fixed, τ_s, τ_r, and ω_r do not change in value during solution.

Fourier transforms are then applied to the five regions to determine the magnitude coefficient and phase angle for each harmonic component. These values are inserted into the scheduled value matrix for the appropriate busses. The algorithm is then allowed to proceed as it normally would.

TEST RESULTS

To demonstrate the theories presented in this paper, the General Dynamics Corporation 20 kHz testbed was used as a source of comparison [7]. The testbed was configured to have a Mapham inverter supply a constant power AC load through a 50 meter transmission line. The Mapham inverter has the following characteristics:

Operating Voltage:	440	V,
System Frequency:	20	kHz,
L_r:	16	μH,
C_r:	1.71	μF,
C_s:	2.0	μF.

The transmission line has the following characteristics:

R:	1.043	m Ω/meter,
L:	0.027	μH/meter,
C:	0.003	μF/meter.

The characteristics of the load are:

Power:	2 - 10	kVA,
p.f.:	80%, lagging.	

The resulting Total Harmonic Distortion (THD) of the bus voltage, defined as

$$THD = \sum_{n=2}^{\infty} \frac{(V_i^{(n)})^2}{V_i^{(1)}} ,$$

was obtained from the harmonic power flow studies and these results are compared with actual test data from the testbed. The results are summarized in Figure 5. A resonable correlation is evident between the experimental results and those obtained from the modified HARMFLO.
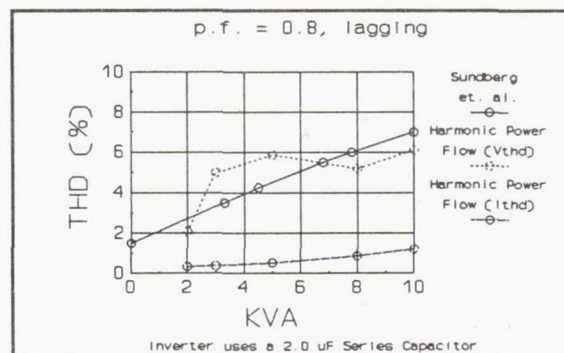

Figure 5 - Comparison of Results of Bus Voltage THD versus KVA Loading from Harmonic Power Flow Program and Test Data from the GDC 20 kHz Testbed. Current THD versus KVA Loading is also included.

CONCLUSIONS

The simulation of harmonic behavior in large spacecraft power systems can now be studied and problems associated with this behavior can be corrected since a major analytical tool needed for this work is now available.

Fine tuning of the system models and their values, via experimental verification, are the items which must be further evaluated so that accurate conclusions can be drawn on the complete validity of the source code. The completion of this evaluation work is scheduled for 1992.

The models used are flexible enough to allow for future changes in system design and operation. The modelling has also been incorporated into HARMFLO with little degradation in the convergence characteristics of the Newton-Raphson method.

The modified HARMFLO can be used for the determination and/or prediction of system interactions such as harmonic resonance and electromagnetic interference (EMI). A future paper will address these issues.

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